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# Effect of Interface Strength of $M_{23}C_6$ in Steel Matrix on Tensile Toughness and Strength

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## Abstract

Using methods which are applied for estimating strength and toughness of composites reduces rate of trial-and-error in their design. One of the mechanisms for strengthening and increasing toughness of composites is application of reinforcement pull-out mechanism. Interface strength of reinforcement with matrix and effective surface of pulled-out greatly affect toughness and strength of these types of materials. In this study, a model was proposed to estimate interface and matrix strength of composites and share in increasing tensile toughness and strength. Then, strength of interface and its share in increasing tensile toughness and strength were calculated in a case study of composites containing $M_{23}C_6$ particle reinforcement in matrix of 1.2542 tool steel.

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*Keywords:* Design of composites; Particles population density; Strength of interface

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**List of Variables**

$A_{CO}$ = Surface of composite = $1m^2$
$A_{M,ef}$= Effective surface of matrix
$A_{P,\ PO}$ = Effective surface of debonding
$A_{P,ef}$= Effective surface of particle
$\sigma_{M,UTS}$ = Ultimate tensile strength of matrix
$\sigma_{CO,UTS}$ = Ultimate tensile strength of composite
$\sigma_{P,UTS}$ = Ultimate tensile strength of particle
$\sigma_{P,PO}$ = Interface strength
$e_f$ = Fracture strain
$\Delta L_{CO}$ = Elongation of composite
L= Length of fiber
R= Particle radius

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## 1. Introduction

Tool steels are used to form other materials. High-performance tool steels have high strength, high hardness, high abrasion resistance, high toughness and reasonable price. In general, hardness and strength are inversely related to toughness, which limits application of tool steels. In order to overcome this problem, engineers have started to produce composites with hard and abrasion resistant reinforcements. Factors such as adequate strength for the interface between reinforcement and matrix have challenged successful production of this type of material. Furthermore, uniformity of properties in these materials is required for using very fine reinforcements that are finer than one micron and are highly dispersed; this issue leads to problems like agglomeration of reinforcement by Cory (2000) whereas deep cryogenic treatment on AISI M2 and AISI H13 tool steels leads to improvement of abrasion, and sometimes mechanical, properties, which becomes more economical than conventional heat treatment by totally 50% by Mohan et al. (2001). Additionally, similar to behavior of composites, scanning electron microscopy (SEM) image of pulling out $M_{23}C_6$ particles from matrix of 45WCrV7 by Vahdat et al. (2013) and AISI D2 by Das and Ray (2012) tool steels which is deep cryogenic treated and SEM image of breaking down $M_7C_3$ particles have been observed by Das and Ray (2012). In this regard, it has been also observed that, in force-displacement (F-ΔL) curve of deep cryogenic treated 1.2542 tool steel, the elastic part contains several slopes by Farhani et al. (2012). Therefore, deep cryogenic treatment can be used on tool steels to generate a behavior similar to that of composites so that properties are improved considering economic issues. That is because this behavior is caused by the presence of reinforcement of $M_{23}C_6$ particles which are very fine and have scattered distribution in relatively soft matrix of tool steel so that $M_{23}C_6$ particles are precipitated in situ in deep cryogenic treatment.

All researchers have reported increased hardness and abrasion resistance in deep cryogenic treatment whereas some of them have mentioned decreased toughness by Mohan et al. (2001) and by Das and Ray (2012) and some others have reported its increase by Vahdat et al. (2013). These differences are attributed to activation of pull-out mechanism of $M_{23}C_6$ particles in relatively soft matrix of the tool steel so that toughness increase has been reported in a condition in which interface strength of reinforcement with matrix has been appropriate and effective surface of reinforcement has been high; also, toughness decrease has been reported in a condition in which interface strength of reinforcement with matrix has not been suitable and/or effective surface of reinforcement has been low. The reason is that, as far as toughness and strength of these types of materials are concerned, interface strength of reinforcement with matrix and effective surface of pulled-out reinforcement are highly effective by Arsenault et al. (1994). As a result, the reason for these differences is in the fact that optimum conditions have not be obtained for creating appropriate strength of matrix interface with reinforcement and relatively high effective surface for pulled-out reinforcement.

The focus of this study was on studying interface strength of reinforcement of $M_{23}C_6$ particles in matrix of 1.2542 tool steel so that its method could be generalized. Moreover, in case pulled-out mechanism was active, how much would be the share of this mechanism in increasing strength and tensile toughness?

Using methods which are utilized for calculating strength and toughness of composites, trial-and-error rate was reduced in experimental production and design of these types of materials. Many models have been presented for estimating strength and toughness of composites with metal matrix and particle reinforcement. For instance, for the composite with aluminum matrix reinforced with 10 and 20% volume of alumina in similar conditions, fracture toughness ratio has been reported to be in proportion to distance between the particles by Chawla and Allison (2001). It means that, in a particular composite with similar interface in which volume fraction of particles is constant, the finer the particles, the less the distance between the particles would be; so, fracture toughness ratio would be reduced**.** Nardone and Prewo estimated strength of composites with particle reinforcement by proposing an improved shear-lag model by Nardone and Prewo (1986). Shen et al. (2000) used limited elements methods for composites with particle reinforcement to demonstrate that particles' form had no significant impact on their tensile strength. They indicated that, in a composite with aluminum matrix (3.5% age hardened copper containing 20% volume of reinforcement) in similar conditions, strength decreased with cylindrical, spherical, defective cylindrical and two truncated cones, respectively. In Hahn and Rosenfield's model, fracture toughness had direct relationship with size of particles, Young's modulus and yield strength of composite and inverse relationship with volume percent of particles by Bhaskar (2000). In Garrett and Knott's model, fracture toughness had direct relationship with work hardening, Young's modulus and yield strength of composite by Bhaskar (2000).

The aforesaid models by Bhaskar (2000), Chawla and Allison (2001), Nardone and Prewo (1986) and Shen et al. (2000) were not based on microstructure; i.e., in these models, effect of particles population density and interface strength were not considered on load transfer. Therefore, interface strength between reinforcement particles and matrix and also effective surface of pulled-out particles were the research variables. In case of determining interface strength of reinforcement with matrix in certain operating conditions and by controlling population density, size and value of reinforcement, strength and desired tensile toughness could be designed.

## 2. Material and Methods

In this study, 1.2542 tool steel was utilized to calculate interface strength of reinforcement of $M_{23}C_6$ particles in matrix of tool steel. 1.2542 tool steel is usually used for manufacturing cutting blade of thick sheets and as punch of cutting mold. Accordingly, presenting a model for designing tensile toughness and strength of 1.2542 tool steel in impact loading conditions becomes important in practical terms. Its chemical composition is listed in Table 1.

Table 1. Chemical analysis of the 1.2542 tool steel

| Element | (%) | Element | (%) | Element | (%) |
|---|---|---|---|---|---|
| C | 0.48 | S | 0.02 | W | 1.57 |
| Mn | 0.34 | V | 0.02 | Si | 1.00 |
| Cr | 1.12 | P | 0.06 | Fe | Rest |

In this study, the specimens were specifically coded. The first two digits represented duration of soaking at deep cryogenic treatment temperature (-196C) and the last digit represented tempering time at 200C. For instance, the specimen with code 361 meant being soaked at deep cryogenic treatment temperature (-196C) for 36 h and tempered for 1 h at 200C.

To calculate interface strength, 9 sets of specimens, each of which including three specimens, were used in order to provide sufficient data for desirable conclusion and discussion. To determine microstructure characteristics, the cylindrical specimens were 12 mm in diameter and 15 mm in length. TESCAN MIRA II device was used to prepare images of SEM. In addition, OLYSIA m3 metallographic software which was calibrated for 2048 × 1536 pixels was utilized for phase analysis of SEM images. For calculating each phase, at least 5 SEM images with magnification of $10^4$ from one region were used. Mean of the data is reported in Table 2. In accordance to BS EN 10002-1 (2001), tensile test specimens were prepared in dumbbell shape with diameter (d) of 5 mm, initial base length (L) of 25 mm and total length ($L_t$) of 15 cm; its results are shown in Table 3. Tensile test was performed in strain rate of $0.00166s^{-1}$. Before deep cryogenic treatment, specimens' machining was implemented using a CNC milling device. The procedural steps are demonstrated in Fig. 1.

### 2.1. Theory

To present a model for strength and tensile toughness of composites with particle reinforcement in which pull-out mechanism is dominant (Fig. 2), if particles break down, the maximum effective surface is equal to a surface of the particle which passes the diameter and is equal to area of the circle for spherical particles (Fig. 2(a)). According to Fig. 2(b), if particles are pulled-out of the matrix (without being broken down), effective surface of the particle is equal to its perimeter and is equal to surface of a sphere in spherical particles. It means that, when pull-out mechanism is dominant, effective surface of particles increases for strengthening because area of circle ($\pi r^2$) of each spherical particle is smaller than sphere surface ($4\pi r^2$). Thus, three conditions may occur for strengths of matrix, reinforcement and their interfaces.

Table 2. Content, average size and PD of $M_7C_3$ and $M_{23}C_6$ particles for 1.2542 tool steel

| Specimen code | $M_7C_3$ content V% | $M_{23}C_6$ content V% | $M_7C_3$ average size µm | $M_{23}C_6$ average size µm | PD of $M_7C_3$ $mm^{-2}$ | PD of $M_{23}C_6$ $mm^{-2}$ |
|---|---|---|---|---|---|---|
| 241 | 0.42 | 2.18 | 0.5 (0.3to1) | 0.22 (0.065to0.5) | 62000 | 660000 |
| 242 | 0.47 | 2.42 | 0.55 (0.3to1) | 0.23 (0.065to0.5) | 65000 | 630000 |
| 243 | 0.37 | 3.73 | 0.7 (0.6to0.9) | 0.28 (0.065to0.7) | 60000 | 600000 |
| 361 | 0.57 | 4.69 | 0.65 (0.5to0.8) | 0.30 (0.065to1) | 64000 | 894000 |
| 362 | 0.60 | 6.92 | 0.7 (0.4to1.7) | 0.35 (0.065to0.7) | 63000 | 750000 |
| 363 | 0.34 | 8.91 | 0.7 (0.4to1.5) | 0.40 (0.065to0.6) | 62000 | 726000 |
| 481 | 0.35 | 10.04 | 0.7 (0.3to1.4) | 0.24 (0.065to0.7) | 65000 | 707000 |
| 482 | 0.25 | 12.66 | 0.7 (0.4to1.4) | 0.5 (0.065to1) | 62000 | 650000 |
| 483 | 0.24 | 12.87 | 0.7 (0.4to2) | 0.52 (0.065to1) | 65000 | 620000 |

Table 3. Results of tensile test at room temperature for 1.2542 tool steel

| Specimen code | $\sigma_{CO,UTS}$ MPa | $\Delta L_{CO}$ mm | $U_T$ (MJ)= by Dieter (2000) $2/3\times\sigma_{M,UTS}\times\Delta L_{CO}/50\times100$ |
|---|---|---|---|
| 241 | 2279±21 | 2.4±0.37 | 72.2 |
| 242 | 2265±31 | 1±0.5 | 30.2 |
| 243 | 2137±53 | 3±0.75 | 85.5 |
| 361 | 2268±65 | 3.5±0.75 | **105.9** |
| 362 | 2201±65 | 2.5±0.75 | 73.4 |
| 363 | 2245±65 | 2.5±0.75 | 74.8 |
| 481 | 2244±64 | 3.1±0.15 | **92.8** |
| 482 | 2206±65 | 3.8±0.75 | **110.3** |
| 483 | 2249±28 | 3.1±0.4 | **93.0** |

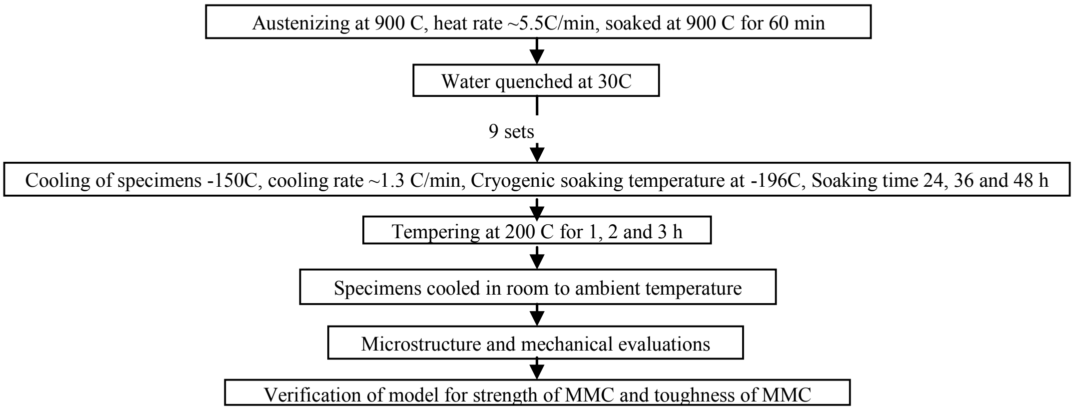

Fig. 1. Procedures of calculating interface strength of $M_{23}C_6$ particles in matrix of 1.2542 tool steel and determining share of pulling-out $M_{23}C_6$ particles in matrix of 1.2542 tool steel for increasing strength and tensile toughness

### 2.1.1 When particle strength is less than that of matrix and interface

Stress is distributed in all parts of composite. Since particle has less strength, first, the particle is broken down. As the particle breaks down, interface will have no role in strengthening composite. Then, the matrix will resist until the composite is broken down; thus, strength of composite is obtained using Equations (1) to (3).

$$\sigma_{CO,UTS} \times A_{CO} = (\sigma_{P,UTS} \times A_{P,ef}) + (\sigma_{M,UTS} \times A_{M,ef}) \quad (1)$$

$$A_{P,ef} = PD \times \pi r^2 \quad (2)$$

$$A_{CO} = A_{P,ef} + A_{M,ef} \rightarrow A_{M,ef} = A_{CO} - PD \times \pi r^2 \quad (3)$$

By substituting Equations (2) and (3) in Equation (1), Equation (4) is obtained as follows:

$$\sigma_{CO,UTS} = (\sigma_{P,UTS} \times PD \times \pi r^2) + (\sigma_{M,UTS} \times (1 - PD \times \pi r^2)) \quad (4)$$

Tensile toughness is the amount of work per volume unit of material before rupturing. Since particles are hard and brittle, their tensile toughness can be neglected. Interface plays no role in this case. Therefore, tensile toughness of total composites which are in condition "A" is obtained by Equation (5). If $\Delta L_{CO}$ is in meter and force ($F_M = \sigma_{M,UTS} \times A_{M,ef}$) is in Newton, tensile toughness unit will be in Joule.

$$U_T \equiv \sigma_{M,UTS} \times A_{M,ef} \times \Delta L_{CO} = \sigma_{M,UTS} \times (A_{CO} - PD \times \pi r^2) \times \Delta L_{CO} \quad (5)$$

In this condition, using another method (according to Equation (6) by Dieter (2000)), tensile toughness can be calculated more accurately. In specific volume of composite, increased volume of particles reduces matrix volume; since according to Equation (6) by Dieter (2000), only tensile toughness of matrix affects tensile toughness of composite, thus, tensile toughness of composite is also reduced. Therefore, the same conclusion is obtained in Equation (5).

$$U_T \approx 2/3 \times \sigma_{M,UTS} \times e_{f,CO} \quad \text{and} \quad e_{f,CO} = \Delta L_{CO}/50 \times 100 \quad (6)$$

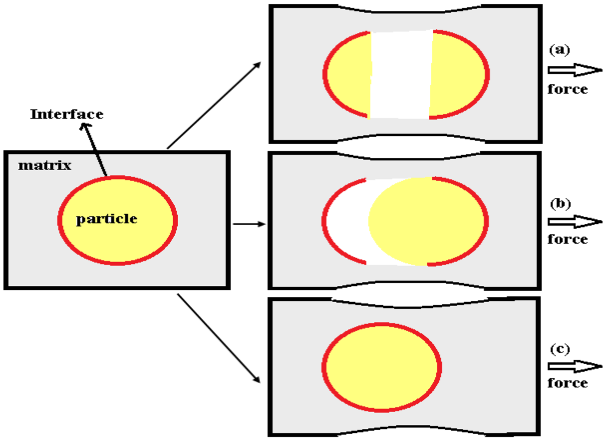

Fig. 2. Effective surface for strengthening (a) when the particles break down; (b) when the particle is pulled out

### 2.1.2 When interface strength is less than that of matrix and particle

Interface has less strength; so, as long as particles are pulled out of the matrix, the matrix along with pull-out mechanism of particles plays a role in strengthening. Therefore, strength of composite is obtained from Equations (3), (7) and (8). When the particles are pulled out of the matrix, it will only resist until the composite is broken down.

$$\sigma_{CO,UTS} \times A_{CO} = (\sigma_{P,PO} \times A_{P,PO}) + (\sigma_{M,UTS} \times A_{M,ef}) \quad (7)$$

$$A_{P,PO} = PD \times 4\pi r^2 \quad (8)$$

By substituting Equations (3) and (8) in Equation (7), simplified Equation (9) is obtained.

$$\sigma_{CO,UTS} = (\sigma_{P,PO} \times PD \times 4\pi r^2) + (\sigma_{M,UTS} \times (A_{CO} - PD \times \pi r^2)) \quad (9)$$

Tensile toughness is the amount of work per volume unit of material before rupturing. Considering Equation (10), it could be regarded as equivalent to the product of multiplying the force required for deformation by the length of pathway through which the particle is drawn in the matrix. If force is in Newton (Force = σ × A) and the pathway is in meter, tensile toughness unit is in Joule. Note that, the length of pathway through which the particle is drawn in the matrix ($2\pi \times r$) is in proportion to particle size. Considering Table 2, size of particles is very small (from 0.065 to 2 micron) and is less than $\Delta L_{CO}$.

$$U_T \equiv (\sigma_{P,PO} \times A_{P,PO} \times 2\pi r) + (\sigma_{M,UTS} \times A_{M,ef} \times \Delta L_{CO}) \quad (10)$$

By substituting Equations (3) and (8) in Equation (10), simplified Equation (11) is obtained for tensile toughness calculation.

$$U_T \equiv (\sigma_{P,PO} \times PD \times 8\pi^2 r^3) + (\sigma_{M,UTS} \times (A_{CO} - PD \times \pi r^2) \times \Delta L_{CO}) \quad (11)$$

### 2.1.3 When matrix strength is less than that of particle and interface

Since matrix has less strength, it will be deformed. As long as the imposed stress does not reach strength of particle or interface, the matrix is deformed along with immobile particles (nailed to the matrix). Therefore, effective surface is matrix surface. In this condition, the higher the population of particles, the less the strength and tensile toughness of composite would be; that is because particles and their interfaces have no role in strengthening. Therefore, strength of composite is obtained from Equation (12).

$$\sigma_{CO,UTS} \times A_{CO} = \sigma_{M,UTS} \times A_{M,ef} \quad (12)$$

By substituting Equation (3) in Equation (12), simplified Equation (13) is obtained.

$$\sigma_{CO,UTS} = \sigma_{M,UTS} \times (A_{CO} - PD \times \pi r^2) \quad (13)$$

Tensile toughness is the amount of work per volume unit of material before rupturing. So, considering the aforesaid points of this condition, tensile toughness is obtained using Equation (14).

$$U_T \equiv \sigma_{M,UTS} \times A_{M,ef} \times \Delta L_{CO} \quad (14)$$

By combining Equations (3), (13) and (14), simplified Equation (15) is obtained for calculating tensile toughness.

$$U_T \equiv \sigma_{M,UTS} \times (A_{CO} - PD \times \pi r^2) \times \Delta L_{CO}) = \sigma_{CO,UTS} \times A_{CO} \times \Delta L_{CO} \quad (15)$$

### 2.1.4 Analysis of theory

In condition "A", since strength of particles is less than that of matrix, according to Equation (4), with increased particles population density, strength is reduced. On the other hand, considering Equation (5), increasing particles population density reduces effective surface of matrix so that tensile toughness of composite is also decreased. Therefore, condition "A" simultaneously leads to reducing strength and tensile toughness and is not appropriate for engineering applications.

In condition "C", according to Equation (13), with increased particles population density, strength is reduced. On the other hand, according to Equation (15), with increase in particles population density, effective surface of matrix is reduced; so, tensile toughness of composite is also reduced. Thus, condition "C" simultaneously results in reduced strength and tensile toughness and that is why it is not suitable for engineering applications.

Using the data in Table 3 and comparing Equations (5) and (15) with Equation (6), equality coefficient of Equations (5) and (15) is calculated as equal to 13.3333.

In equal conditions, tensile toughness of composites which are described as condition "B" is higher than that of composites which are described in conditions "A" and "C" as much as the first statement of Equation (10), i.e. ($\sigma_{P,PO} \times A_{P,PO} \times 2\pi r$), is concerned. This difference increases with increasing effective surface area of the pulled-out particles or surface area of interface ($A_{P,PO}$) and increased interface strength ($\sigma_{P,PO}$). That is why equality coefficient for Equation (11) is more than equality coefficients of Equations (5) and (15). But, how much? Using data of Tables 2 and 3 and comparing Equations (11) and (6), equality coefficient of Equation 11 can be calculated with good approximation (error of 0.00025%) as equal to 14.7.

The first statement of Equation (11) ($\sigma_{P,PO} \times PD \times 8\pi^2 r^3$) is in fact share of reinforcement pull-out mechanism in increasing tensile toughness and the first statement of Equation (9) ($\sigma_{P,PO} \times PD \times 4\pi r^2$) is in fact share of reinforcement pull-out mechanism in increasing strength.

## 3. Results and Discussion

$M_7C_3$ particles were broke down but $M_{23}C_6$ particles were pulled out; so, effects of $M_7C_3$ particles on calculating tensile toughness and strength based on pull-out mechanism were neglected. Additionally, volume fraction of $M_{23}C_6$ particles was much greater than that of $M_7C_3$ particles. On the other hand, conditions "A" and "C" never happened. In condition "B", four factors contributed to increased tensile toughness and strength of the studied composite, which included matrix strength, interface strength, matrix surface and interface surface.

The amount of pulled-out surface which plays a role in strengthening was calculated for $M_{23}C_6$ particles using Equation (8) per square meter of composite surface ($A_{CO}$=1m$^2$), as listed in Table 4. Effective surface of the matrix was obtained by subtracting composite surface (1m$^2$) from total surface of particles (Equation (3)), as given in Table 4. Accordingly, values of two factors were determined. According to the data in Tables 2 and 3, for condition "B", by solving Equations (9) and (11) in a system of two Equations with two unknowns, two other factors of matrix strength ($\sigma_{M,UTS}$) and interface strength ($\sigma_{P,PO}$) were determined based on Equations (16) and (17), the values of which are listed in Table 4.

$$\sigma_{P,PO} = (\sigma_{CO,UTS} - \sigma_{M,UTS} \times (1 - PD \times \pi r^2)) / (PD \times 4\pi r^2) \qquad (16)$$

$$\sigma_{M,UTS} = ((U_T/14.7) - 2\pi r \times \sigma_{CO,UTS}) / ((\Delta L_{CO} - 2\pi r) \times (1 - PD \times \pi r^2)) \qquad (17)$$

Share of pull-out mechanism of $M_{23}C_6$ particles in matrix of 1.2542 tool steel in tensile toughness increase, i.e. the first statement of Equation (11), was calculated and recorded in Table 4, which was negligible, since particle reinforcements had small effective surface for tensile toughness ($PD\times4\pi r^2\times2\pi r$) whereas fiber reinforcements had much larger effective surface for tensile toughness ($PD\times2\pi rL/2\times L/2$). For example, in equal conditions, if fiber length was at least 300 times of fiber radius ($L=300\times r$), then effective surface for tensile toughness would be at least equal to 1800 ($\approx300^2/16\pi$). However, share of pull-out mechanism of $M_{23}C_6$ particles in matrix of 1.2542 tool steel in increasing strength, i.e. the first statement of Equation (9) (in accordance to Table 4), would be 9.3%, which was considerable.

Table 4. Pulled-out surface, matrix surface, strength of matrix, strength of interface and share of pull-out mechanism in increasing strength and tensile toughness

| Specimen code | $A_{P,PO}$ mm$^2$ | $A_{M,ef}$ mm$^2$ | Matrix strength | Interface strength | Effect of reinforcement pull-out mechanism in increasing tensile toughness or the first statement of equation 11 ($\sigma_{P,PO} \times PD \times 8\pi^2 r^3$) | Effect of reinforcement pull-out mechanism in increasing strength or the first statement of equation 9 ($\sigma_{P,PO} \times PD \times 4\pi r^2$) |
|---|---|---|---|---|---|---|
| 241 | 100304 | 974924 | 2099 | 2317 | -------------- | -------------- |
| 242 | 104647 | 973838 | **2109** | **2012** | 2238J (0.007%) | 211MPa (9.3%) |
| 243 | 147706 | 963074 | **2012** | **1344** | 2570J (0.003%) | 199MPa (9.3%) |
| 361 | 252644 | 936839 | **2195** | **834** | 2922J (0.003%) | 211MPa (9.3%) |
| 362 | 288488 | 927878 | **2151** | **709** | 3309J (0.005%) | 205MPa (9.3%) |
| 363 | 364742 | 908814 | **2240** | **572** | 3857J (0.005%) | 209MPa (9.3%) |
| 481 | 429788 | 892553 | **2280** | **485** | 4241J (0.005%) | 209MPa (9.3%) |
| 482 | 510250 | 872438 | **2293** | **402** | 4738J (0.004%) | 205MPa (9.3%) |
| 483 | 526415 | 868396 | **2349** | **397** | 5024J (0.005%) | 209MPa (9.3%) |

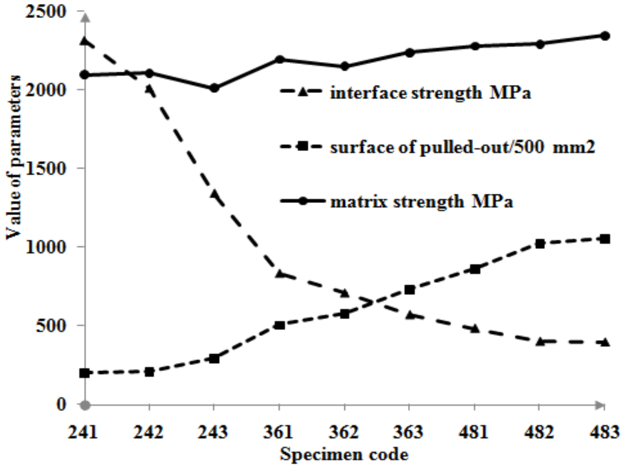

Fig. 3. Comparing pulled-out surface, matrix strength and interface strength for 9 different specimens

In Fig. 3, in all the specimens except specimen 241, strength of interface was less than that of the matrix. This issue provided the field for pulling out particles; i.e. it was in agreement with the initial assumption that was governing condition "B". On the other hand, with increasing time of deep cryogenic soaking or tempering time, interface strength was being reduced because, with increasing deep cryogenic soaking or tempering times, size of $M_{23}C_6$ particles became larger (according to Table 3); larger particle decreased coherency of interface, which reduced strength of the interface.

According to Table 2, with increasing time of tempering or soaking, the amount of secondary carbide constantly increased. Thus, the matrix metal around the carbide had poor carbon and alloying elements. Accordingly, the matrix which was poor of carbon and alloying elements could have an effective role in increasing tensile toughness.

For strength, the above finding was confirmed in Fig. 3, with an increase in tempering or soaking times, strength of metal matrix is almost constant. Therefore, strengthening of debonding mechanism had the significant effect on strength of composite.

This method can be generalized to the composite with fiber reinforcement. In such a state, Equations (16) and (17) can be changed as Equations (18) and (19).

$$\sigma_{fiber,PO} = (\sigma_{CO,UTS} - \sigma_{M,UTS} \times (1 - PD \times \pi r^2)) / (PD \times \pi DL/2) \quad (18)$$

$$\sigma_{M,UTS} = ((U_T/K) - L/2 \times \sigma_{CO,UTS}) / ((\Delta L_{CO} - L/2) \times (1 - PD \times \pi r^2)) \quad (19)$$

Whereas D is fiber diameter, L is fiber length and K is equality coefficient of Equation 11.

## 4. Conclusions

In this study, a model was proposed for designing tensile toughness and strength of composites based on reinforcement pull-out mechanism. This model was utilized for 9 specimen sets of 1.2542 tool steel with $M_{23}C_6$ particle reinforcement which was precipitated in situ in deep cryogenic treatment. Considering average diameter of spherical particles, it was concluded that, in most of the specimens (all the specimens except specimen 241), interface strength (from 2012 to 397 MPa) was less than that of matrix (from 2012 to 2349 MPa) and reinforcement; so, conditions were prepared for activating pull-out mechanism of reinforcement. Also, for the discussed 1.2542 tool steel, share of pull-out mechanism of $M_{23}C_6$ particles was negligible in tensile toughness increase (from 0.003 to 0.007%); but, its share in strength increase was considerable (9.3%).

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